Electro-Thermo-Mechanical Responses of Conductive Adhesive Materials

Kai X. Hu, Chao-Pin Yeh, and Karl W. Wyatt

Abstract—**Micromechanics models which aim to provide an understanding of conductive adhesive materials from the level of micro-particles (less than 30 mm) are presented in this paper. The pressure-induced conducting mechanisms are investigated. A deformation analysis reveals a logarithmic pressure-resistance relationship and is capable of addressing the conducting phenomena for both rigid and deformable particle systems within a contact mechanics framework. This logarithmic relationship also provides analytical support for findings reported in the literature of conductive adhesive research. It is observed that electrical contacts are made by squashing conducting particles for a deformable particle system while the particle penetration creates a crater in metallization to make contacts for a rigid particle system. The current analysis provides simple closed-form solutions for the elastic deformation of single-particle contacts and based on the assumption that the contact forces are evenly distributed in a conductive film, the pressure-resistance responses are correlated to the particle volume fraction. The high volume fraction, while ensuring that there are a sufficient number of particles to make contacts, may limit the particle deformation due to overall increased stiffness, resulting in the increased resistance on a per particle basis. The current analysis also offers insight into design considerations whereby limited amount of deformation (low processing temperature) and sufficiently low electrical resistance are to be simultaneously satisfied. For the mechanical performance, the uniaxial nonlinear stress–strain relationship is obtained for conductive adhesive systems in terms of polymer and particle material properties. The Mori–Tanaka's method is utilized to account for particle–particle and particle–matrix interactions. The behavior in thermal expansion within the elasto-plastic deformation range is also obtained in a similar fashion. In all these calculations, only a very simplified finite element analysis for the problem of a particle embedded into an infinitely extended matrix material needs to be carried out.**

Index Terms—**Conductive adhesive, contact resistance, thermal expansion.**

I. Introduction

POLYMER-BASED conductive adhesive materials have been widely used in a number of interconnect applications, including, for example, wire bonding, tape automated bonding, and direct chip attachment (chip on glass, chip on ceramics, flip chip on board, etc.). Using conductive adhesives as interconnect materials offers certain advantages in terms of reduced package size and thickness (finer pitch), improved environmental compatibility, and lowered assembly temperature. A conductive adhesive material is by nature a composite consisting of a matrix material (normally thermosetting epoxy) and conducting particles that are dispersed in the matrix material. During the assembly, the epoxy resin is being cured to provide mechanical (and some times thermal) interconnective functions and particles are utilized for electrical connections. The variations from one system to another include matrix and particle compositions (particle loading, shape) and particle treatments (coated or uncoated), curing agents, and curing characteristics. These broad variations of a conductive adhesive system, along with variations of substrate, module and perspective metallizations, offer a versatile selection of interconnection configurations. Based on common, current industry practice, conductive adhesive materials can be classified into two categories, anisotropic (Z-axis) conductive adhesives (ACA) and isotropic conductive adhesives (ICA). The anisotropic conductive adhesives provide electrical conductivity in a specific direction, normally in the thickness direction (Z-axis) for conductive films. The isotropic conductive adhesives are electrically conductive in all directions and are normally applied in the form of joints as opposed to the anisotropic materials in the form of films.

An extensive body of literature on conductive adhesives exists (e.g., [3]–[6], [8], [12], [17], [18], and [23]). For anisotropic conductive adhesives, the focus has been on the electrical performance in terms of DC and AC resistance and conductance. It is also observed that there are two types of conducting mechanisms. For a rigid particle system, particles penetrate into conducting patterns to make contacts, forming interconnect, while for a deformable particle system, the contacts are achieved mostly by particle deformation (the definition of rigid and deformable particles will be given later in our deformation analysis). The electrical resistance is a function of compressive force applied during the assembly (the force is removed and electrical contacts are kept after cure). The force-resistance relationship were studied by [8], [19], and [20]. In the work by [19], a conceptual design curve that compromises the electrical contact and particle deformation is outlined. The experimental data by [8] for elastomeric polymer-based material with conducting columns and by [20] for elastomer with carbon particles showed an inverse relationship between electrical resistance and applied pressure. Reference [20] went as far as suggesting that resistance decreases with increasing pressure in a logarithmic manner for the conductive polymer pressure sensor application. Such

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The authors are with Applied Simulation and Modeling Research, Motorola Inc., Schaumburg, IL 60196 USA.

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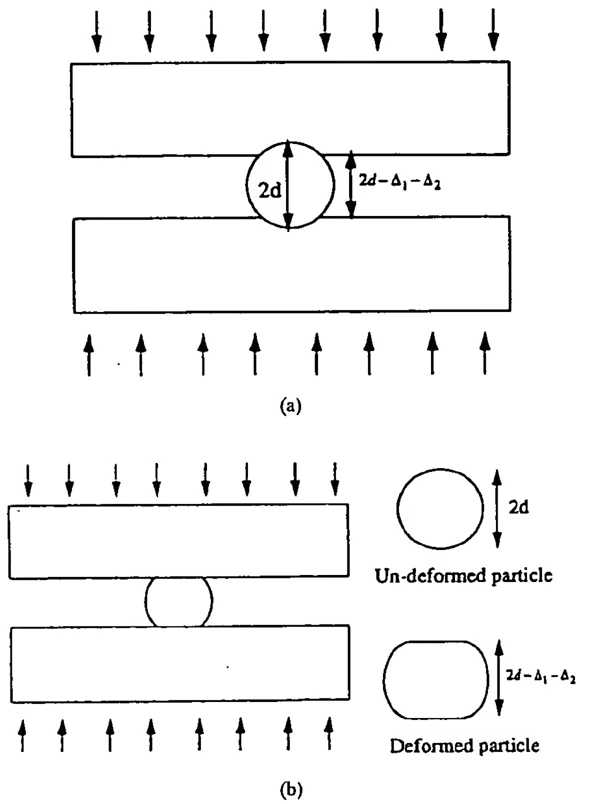


Fig. 1. (a) Schematics of a rigid particle system and (b) schematics of a deformable particle system.

a logarithmic relationship has not been explained on a rigorous, analytical ground. Conductive mechanism considered to date argues that there is a microscopic bumps, acting as parallel resistive switches that turn on at a varying small pressure. When the film is pressed against the conductive patter, more and more bumps come in contact and cause resistance to decrease. There is a semi-empirical equation to relate the resistance with material hardness into the equation [10]. This semi-empirical relationship does not provide any contact physics (particle deformation, applied force, etc.) nor it shed lights regarding the differentiation of rigid and deformable particle systems. Of the same importance as electrical resistance is mechanical performance of conductive adhesives under service and pre-qualification testing conditions. The definition of ACA and ICA becomes vague when the mechanical responses of conductive adhesives are considered. An ICA material becomes anisotropic when the particles or flakes are settled during cure while an ACA material is essentially in-plane isotropic. The nonlinear thermo-mechanical responses due to particle nonlinear deformation are critical for understanding the mechanical performance of conductive adhesive materials.

In this paper, we present a micromechanics approach for conductive adhesive materials. A contact mechanics model is first proposed that addresses pressure-induced conducting mechanisms both for rigid and deformable particle systems. The nonlinear thermo-mechanical responses of conductive adhesive materials are then investigated in terms of polymer and particle properties. An outline of the paper is as follows. In Section II, we set out a deformation analysis that incorporates conducting mechanisms and based on that, a subsequent force-resistance relationship is established in Section III. For the linear elastic deformation, the solution is given in the closed-form and reveals a logarithmic pressure-resistance relationship. For plastic deformation, detailed finite element analysis is given. This result provides an analytical support for experimental data obtained by [8] and [20]. Section IV gives a uniaxial stress–strain relationship of conductive adhesive material using a micromechanics model, the Mori–Tanaka's method and Section V investigates the thermal expansion behavior. A brief summary of the results are given in Section VI.

II. Deformation Analysis

Deformation-resistance relationship are considered in this section. The electrical contacts are achieved in most conductive adhesive systems by simultaneously applying force and temperature. The objective of compressive force is to make the mechanical engagement between conductive particles and metallization, and after curing at the temperature of about 150 °C, the permanent irreversible deformation provided by the compressive force remains in the system to secure electrical contacts. Two types of mechanical contacts are reported:

1) rigid particle system, in which, the particle deformation is very limited and the contacts are created through indentation of particles into metallization;
2) deformable particle system, in which, particles are squashed to form a flat surface, making electrical contacts with metallization through the areal interface on the flat surface.

In the deformable particle case, metallization takes little plastic deformation compared to the particles. In a practical material system, the absolute rigid particle or rigid metallization is just an idealization. But all the material systems will be bounded in between these two extremes and an examination of such systems will provide enough insights to conducting mechanisms. A case in which both particle and metallization deform plastically will be considered later. During the assembly process, epoxy matrix are in a liquid state and can be assumed not to take any mechanical load. The schematics of making contacts by applying compressive force to a single particle system (multi-particle scenario will be discussed later) are shown in Fig. 1(a) for rigid particle system and in Fig. 1(b) for deformable particle system. It should be noted that a conductive joint is typically formed by applying a pressure at curing temperature. During that process, polymer matrix is in a gelatiniform and bears little load-carrying capacity. Therefore, as long as the particle deformation is concerned, one can treat the adhesive joint as a distributed particles only since the matrix does not sustain any loading.

In what follows, we show that the two types of conducting mechanisms can be treated in a similar fashion. First, the rigid particle system is considered [shown in Fig. 1(a)]. Assuming the particle indentation does not change the resistance of metallization, the particle radius of r are indented into the lower trace and upper pad of the depths of Δ_1 and Δ_2, the

resistance of the interconnect is

$$\begin{aligned} R &= \int_{-(r-\Delta_1)}^{r-\Delta_2} \rho \frac{dl}{A} \\ &= \int_{-(r-\Delta_1)}^{r-\Delta_2} \rho \frac{dl}{\pi(r^2 - l^2)} \\ &= \frac{\rho}{2\pi r} \ln\left[\left(\frac{2}{\varepsilon_1} - 1\right)\left(\frac{2}{\varepsilon_2} - 1\right)\right] \end{aligned} \tag{1}$$

where ρ is the particle resistivity, $\varepsilon_1 = \Delta_1/r$ and $\varepsilon_2 = \Delta_2/r$. ε_1 and ε_2 measure the magnitude of particle deformation, and can be interpreted as an overall particle strain. For small strain, or $\varepsilon_1 \ll 1$ and $\varepsilon_2 \ll 1$, we have

$$R = \frac{\rho}{2\pi r} \ln\left(\frac{4}{\varepsilon_1 \varepsilon_2}\right). \tag{2}$$

For the case where lower and upper part share the same amount of deformation (symmetric about horizontal plane), $\varepsilon_1 = \varepsilon_2 = \varepsilon$

$$R = \frac{\rho}{\pi r} \ln\left(\frac{2}{\varepsilon} - 1\right) \tag{3}$$

and finally for symmetric and small deformation case

$$R = \frac{\rho}{\pi r} \ln\left(\frac{2}{\varepsilon}\right). \tag{4}$$

For the case of deformable particles, if Δ_1 and Δ_2 are changed to the particle deformation, (1)–(4) shall still hold true. But the cross-sectional area of the particles is enlarged due to Poisson's ratio effect when the conducting particles are deformed by compressive force. The extent to which the area gets widened depends on the cross-sectional location (or x-coordinate). For the bulky resistance calculation, we assume that area enlargement follows an average Poisson's law. The deformed area at location of x become

$$A = \pi(r^2 - l^2)\left[1 + \frac{v(\varepsilon_1 + \varepsilon_2)}{2}\right]^2 \tag{5}$$

where v is the Poisson's ratio of the particle. Accordingly, (1) ought to be modified to account the effect of Poisson's ratio on the resistance, giving

$$R = \frac{\rho}{2\pi r\left[1 + \frac{v(\varepsilon_1 + \varepsilon_2)}{2}\right]^2} \ln\left[\left(\frac{2}{\varepsilon_1} - 1\right)\left(\frac{2}{\varepsilon_2} - 1\right)\right]. \tag{6}$$

Similarly, for the symmetric case where lower and upper particle are compressed to same amount

$$R = \frac{\rho}{\pi r(1 + v\varepsilon)^2} \ln\left(\frac{2}{\varepsilon} - 1\right). \tag{7}$$

Equations (1) and (6) provide a resistance-deformation relationship for rigid and deformable particle systems. When assembly process is deformation-controlled, those equations can be used to estimate how much deformation is required to attain to a desired level of resistance. In real assembly processes, however, the deformation-controlled attachments can hardly be the case and may where it be, the particle deformation can not easily estimated from applied deformation. One would always rather know the amount of compressive force necessary to achieve the desirable contact. In the next section, those equations will be used as an utility to obtain the force-resistance relationship.

III. Force-Resistance Relationship

The force-resistance relationship is derivable based on the deformation analysis presented in Section II. This is done by solving the contact mechanics problem to obtain the force-deformation relationship. The force-deformation relationship can then be substituted into resistance equations to backout the desired force-resistance relationship. In the following, a standard elastic contact solution is utilized to give closed form solutions for both rigid particle and deformable cases, and a more general elastic-plastic contact solution is given in the context of finite element numerical solutions.

A. Elastic Solutions

Consider an elastic spherical particle of Young's modulus E_0 and Poisson's ratio v_0, being in contact with upper and lower metallizations of Young's moduli E_1 and E_2 and Poisson's ratio v_1 and ν_2. The metallizations are assumed to be infinitely extended. The upper metallization are being compressed from the remote by a load that transfers a resultant force of magnitude P to the particle. The elastic solution under small deformation and small sliding contact conditions can be given [9], [16]

$$\Delta_1 = \sqrt[3]{\frac{9}{16r}\left(\frac{1 - \nu_0^2}{E_0} + \frac{1 - \nu_1^2}{E_1}\right)P^2} \tag{8a}$$

and

$$\Delta_2 = \sqrt[3]{\frac{9}{16r}\left(\frac{1 - \nu_2^2}{E_2} + \frac{1 - \nu_0^2}{E_0}\right)P^2}. \tag{8b}$$

Substitution from (8) into (6) (using small deformation assumption) gives

$$R = \frac{2\rho}{3\pi r} \ln\left[\frac{P_0}{P}\right] \tag{9}$$

where P_0 bears a force unit, and depends on particle size and material properties

$$P_0 = \frac{8\sqrt{2}r^2}{\sqrt[3]{\left(\frac{1 - v_0^2}{E_0} + \frac{1 - v_1^2}{E_1}\right)\left(\frac{1 - v_2^2}{E_2} + \frac{1 - v_0^2}{E_0}\right)}}. \tag{10}$$

Equations (9) and (10) can be specialized to various combinations of metallizations and particles. Two such special cases are considered here.

Case 1) Elastic Solutions—Rigid Particle Case: Applying the above equation to the case of rigid particle with upper and lower metallizations of Young's modulus and Poisson's ratio E_1, E_2, and $v_1\nu_2$, the indentation in metallization can be given

$$\Delta_1 = \sqrt[3]{\frac{9}{16r}\left[\frac{(1 - \nu_1^2)P}{E_1}\right]^2} \tag{11a}$$

and

$$\Delta_2 = \sqrt[3]{\frac{9}{16r}\left[\frac{(1-\nu_2^2)P}{E_2}\right]^2}. \tag{11b}$$

This leads to the same force resistance relationship as presented by (9) while P_0 being given as

$$P_0 = \frac{8\sqrt{2}r^2}{3}\sqrt{\left(\frac{E_1}{1-\upsilon_1^2}\right)\left(\frac{E_2}{1-\upsilon_2^2}\right)}. \tag{12}$$

Case 2) Elastic Solutions—Rigid Metallization Case: For the case of rigid metallization, the particle is compressed and the amount of deformation due to the compressive force in upper part of the ball equals that of the lower part of the ball. Therefore, we have a symmetric case

$$\begin{aligned}\Delta_1 &= \Delta_2 \\ &= \sqrt[3]{\frac{9}{16r}\left[\frac{(1-\nu_0^2)P}{E_0}\right]^2}.\end{aligned} \tag{13}$$

That leads to the same form of the solution as given in (9), with P_0 being given as

$$P_0 = \frac{8\sqrt{2}r^2}{3}\left(\frac{E_0}{1-\upsilon_0^2}\right). \tag{14}$$

One can of course consider other combinations, for example, rigid metallization on the top or on the bottom only, etc.

Next, the effect of pressure on electrical resistance is reexamined within the contact mechanics framework. It shall be noted that in published experimental investigations (e.g., [8], [19], and [20]), the resistance is directly related to applied pressure. While this correlation has a direct physical interpretation, it does not shed light on the variation of different systems with different particle volume load, material selection, etc. For example, one would expect to compress a conductive adhesive system with less loaded particles by a much smaller pressure than a system with heavily loaded particles. To put the volume fraction of particles into the perspective, it is recalled that the force in (9) are understood to the force per particle. Assuming the adhesive thickness is equal to diameter of the particle, we can relate the pressure to force per particle

$$p = \frac{3c_p P}{2\pi r^2} \tag{15}$$

where c_p is the volume fraction of particles. Using the results of the single particle analysis, the pressure-resistance relation then becomes

$$R = \frac{2\rho}{3\pi r}\ln\left[\frac{3c_p P_0}{2\pi r^2 p}\right]. \tag{16}$$

It is observed that for the same applied pressure, the lighter loaded particle system gives a better resistance performance per particle. This conclusion while appearing remarkably different from, but is not against the common belief. As a matter of fact, the total resistance of a conductive adhesive film is obtained through a parallel connection of all individual particles, that is

$$\frac{1}{R_{tot}} = \Sigma\frac{1}{R} = \frac{N_{tot}}{R} = \frac{3c_p A}{2\pi r^2 R} \tag{17}$$

where A is the area of the film, that gives

$$R_{tot} = \frac{4r\rho}{9c_p A}\ln\left(\frac{p_0}{p}\right) \tag{18}$$

where p_0 bears a pressure unit and are related to force sustained by a single particle

$$p_0 = \frac{3c_p P_0}{2\pi r^2}. \tag{19}$$

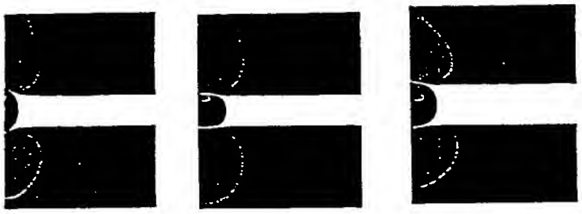
Equations (16) and (18) reveal that while increasing the volume fraction of conducting particles will generally reduce the overall resistance, the resistance per particle base will be increasing for a given pressure.

B. Elasto-Plastic Solutions

Particles and/or metallizations will enter the domain of plastic deformation during the assembly process. The irreversible plastic deformation is very important for the system to remain electrical contact after cure. Also the distinction between rigid particle and deformable particle systems are most appropriately defined in terms of plastic deformation. In a rigid particle system the particle deformation is limited to elastic and a large part of deformation is due to plasticity in metallization. In a deformable particle system, however, the deformation of metallization is limited to the elastic regime and a large part of deformation is due to plasticity in particles. In either case, it is the plastic part of the deformation that makes an overriding contribution to maintaining of electrical contacts since the elastic deformation in principle will be recovered after cure.

To simplify the analysis, we first consider a single particle system [the same system as shown in Fig. 1(a) or (b)] as an axisymmetric problem. The elastic properties are taken as follows: upper and lower metallizations are aluminum and copper with Young's moduli 70 and 132 GPa, and Poisson's ratio 0.35 and 0.34, respectively, and silver particles with Young's moduli 77 GPa, Poisson's ratio 0.30, and particle diameter of 15 μm. For the rigid particle case, the bilinear plasticity of metallizations is considered with yield stress of 36 MPa for aluminum, 56 MPa for copper, secondary slope of 6 GPa for aluminum, and 10 GPa for copper. The system is subjected to a uniform displacement u_z equal to 6 μm at the top of the metallization. The deformation of rigid particle case is shown in Fig. 2(a). For the deformable particle case, the bilinear plasticity of particles is considered with particle yield stress of 172 MPa for aluminum and secondary slope of 7 GPa. The deformation field for the deformable particle case are shown in Fig. 2(b). Also considered is the real conductive adhesive systems with all the participatory materials assuming plastic deformation. The deformation and stress fields for the real material system is shown in Fig. 2(c).

To obtain the force-resistance relationship, the prescribed displacement is gradually increased during several load steps. The resultant force at each load step can be calculated. The particle deformation for the deformable particle case can be extracted from finite element analysis and so can the metallization deformation in metallization for the rigid particle. From this data, the force-deformation relationship



(a) (b) (c)

Fig. 2. Deformation distribution of different particle systems: (a) rigid particle system, (b) deformable particle system, and (c) full deformable system.

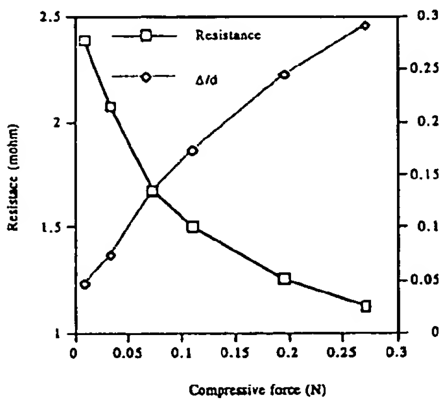


Fig. 3. Force-resistance-deformation relationship for a rigid particle system.

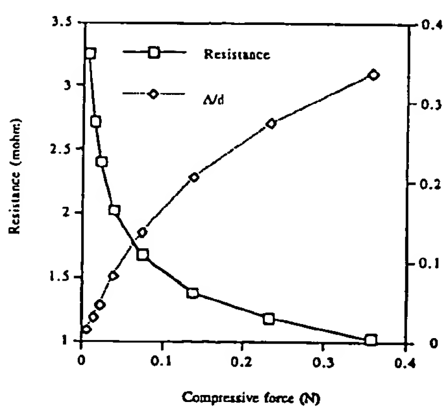


Fig. 4. Force-resistance-deformation relationship for a deformable particle system.

can be obtained directly and the force-resistance relationship can be obtained through (6) and (9) given in Section II. The force-resistance and force-deformation obtained as such are shown in Fig. 3 for the rigid particle case and in Fig. 4 for the deformable particle case. For design consideration the level of applied force should be chosen from this curves in such a fashion that the particle deformation should be limited to ensure the mechanical integrity of the interconnect, but large enough to secure a good electrical contact.

We have so far considered the force-resistance relationship only for a single particle under compression. As a matter of fact, (8) applies to a general system with a restriction that

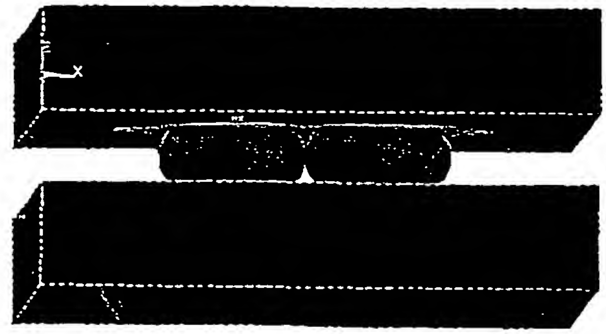


Fig. 5. Deformation distribution of multiple particle systems.

all the particles in the system are assumed to sustain the same amount of forces and the effect of particle interactions on the deformation behavior can be neglected. To examine the effect of particle interactions, a system with two closely spaced two-particles is considered. The distribution of system deformation is shown in Fig. 5. The particles are arranged so close that approaching surfaces will become contacted (multiple contacts) at the same level of particle deformation as for the single particle case. Following the same procedure as that used for the single particle case, it was found that the force-resistance relationship per particle base almost does not change (with more than 94% concurrence of contacts to the single particle results).

IV. Nonlinear Stress–Strain Relationship

The mechanical response, or stress–strain relationship for conductive adhesives after cure are considered here. The system after cure becomes a dual-phase composite material, with conductive particles dispensed in the matrix material. The nonlinear stress–strain behavior for composite materials and similarly for polycrystal materials has been studied by several researchers (see [1], Hutchinson 1970, and [26], for examples). In the following, a micromechanics approach, the Mori–Tanaka's method (e.g., [2], [24]–[26]) will be utilized to investigate the nonlinear behavior of conductive adhesive materials. Our approach presented here follows the same lines as proposed by Weng [26], but in a much simpler context with the interpretation of the micromechanics model. In addition, this approach can accommodate material behavior where nonlinearity can appear instantly (no preceding linear elastic deformation at all). In pursuit of the nonlinear composite behavior, we utilize the Mori–Tanaka's solution for an auxiliary problem, that is, an inclusion embedded into the matrix material subjected to the yet-to-be-determined average matrix a stress in the real composite arising from a designated load. The uniaxial stress–strain is taken as our case study here. Assume that the stress–strain behavior of conductive particles can be presented as

$$\sigma_p = f_p(\varepsilon_p) \tag{20}$$

and that the stress–strain behavior of matrix material

$$\sigma_m = f_m(\varepsilon_m). \tag{21}$$

Let a representative volume of composite material with particle volume fraction of c_p subject to a remote stress σ. This gives rise to the (volumetric) average stress and strain of $\overline{\sigma}_m$ and $\overline{\varepsilon}_m$ in matrix material and $\overline{\sigma}_p$ and $\overline{\varepsilon}_p$ in conductive particles. The average strain in the composite is given

$$\overline{\varepsilon}_c = (1 - c_p)\overline{\varepsilon}_m + c_p\overline{\varepsilon}_p. \qquad (22)$$

One can show that the average stress in composite material is exactly the remote stress σ, regardless of the stress–strain behavior of the matrix and particle materials, that is

$$(1 - c_p)\overline{\sigma}_m + c_p\Sigma(\overline{\sigma}_m) = \sigma \qquad (23)$$

where $\Sigma(\overline{\sigma}_m)$ is the average stress of particles expressed as a function of the average stress of matrix material. Therefore, the determination of composite stress–strain relationship reduces to obtain the values of $\overline{\varepsilon}_c$ for the given remote stress σ. To do that, it is observed that, through (20)–(22)

$$\overline{\varepsilon}_c = (1 - c_p)f_m^{-1}(\overline{\sigma}_m) + c_p f_p^{-1}(\overline{\sigma}_p). \qquad (24)$$

If the average particle stress $\overline{\sigma}_p$ and the average matrix stress $\overline{\sigma}_m$ can be related to the remote stress σ, (24) concludes the stress–strain solution. It is first noted that if one can relate the average stress in matrix material $\overline{\sigma}_m$ to the average particle stress $\overline{\sigma}_p$ through a function Σ

$$\overline{\sigma}_p = \Sigma(\overline{\sigma}_m) \qquad (25)$$

we have via (23)

$$(1 - c_p)\overline{\sigma}_m + c_p\Sigma(\overline{\sigma}_m) = \sigma. \qquad (26)$$

Inversely given a remote stress σ, (26) gives the average matrix stress $\overline{\sigma}_m$ and (25) gives the average particle stress $\overline{\sigma}_p$, and (24) provides the average composite strain $\overline{\varepsilon}_c$ at remote stress σ. This loop provides the solution for stress–strain relationship of the composite. The only thing missing in the loop is the correlation between average matrix stress and the average particle stress. In general, all the particles in the composite are surrounded by matrix material, and the particle stress varies from particle to particle due to particle–particle and particle–matrix interactions. Mori–Tanaka's method [22] recognized that for a composite material subject to a remote stress, the average particle stress can be approximately obtained by embedding a single particle into an infinitely extended matrix material subjected to the average matrix stress. Therefore, a complex problem involving particle–particle and particle–matrix interactions becomes a single particle problem. Equation (25) can be obtained with little computational effort. For linear elastic problems, (25) is given in closed-forms. Since our focus is on the nonlinear response, a simple finite element analysis suffices the task.

As a numerical example, we consider the epoxy-based silver particle system. Epoxy after cure assumes a linear elastic stress–strain relationship and silver particles can be either is elastic or more likely be deformed in a plastic manner, depending assembly processes and service and/or testing conditions (under a typical −55° to 125 °C air to air cycling, particles can show significant plastic deformation). The nonlinear stress–strain curves are shown in Fig. 6. When

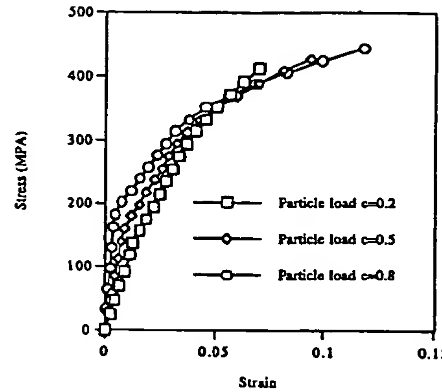


Fig. 6. Uniaxial nonlinear stress–strain curves for a silver-filled epoxy system.

the volume fraction of particles increases, the rigidity of the systems increases accordingly. The cross-over of the curves after strain exceeding 6% is due the current assumption that the epoxy behaves only elastic. In the reality the epoxy matrix becomes yielded and the cross-over cannot happen.

It is also noted that the Mori–Tanaka's method utilized here possesses some limitations. Although the method bears a very good accuracy for particle volume fraction as high as 90% when the ratio of particle to matrix shear modulus falls between 0.5 and 100, which is definitely the case for most adhesive systems [13], [24]–[26], the accuracy decreases significantly as particles become nearly rigid (very high ratio of particle to matrix shear modulus) or become a void [7], [11], [14].

V. Thermal Expansion

The effective thermal coefficient of expansion (CTE) and thermal stress for conductive adhesive systems subject to a temperature change are considered in this section. When the conductive adhesive system is subject to a temperature change ΔT relative to the reference state, the volumetric change is, viewing from the composite level

$$\varepsilon_{ij}^c = 3\overline{\alpha}\Delta T\delta_{ij}. \qquad (27)$$

The average strain, viewed from two individual phases, the particles and the matrix, is given

$$\varepsilon_{ij}^c = c\varepsilon_{ij}^i + (1 - c)\varepsilon_{ij}^m. \qquad (28)$$

Assuming that the matrix material behavior obeys the linear elastic law and the nonlinearity of the adhesive system stems solely from the deformation plasticity of conducting particles. The stress–strain relationship for matrix are

$$\varepsilon_{ij}^M = \frac{1 + \nu_M}{E_M}\sigma_{ij}^M - \frac{\nu_M}{E_M}\sigma_{kk}^M\delta_{ij}. \qquad (29)$$

And, the total stress–strain form for particles can be given as

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{\nu_I}{E_I}\sigma_{kk} - \alpha_I\Delta T\right)\delta_{ij} + \varepsilon_{ij}^p \qquad (30)$$

where for the deformation theory, plastic strain, ε_{ij}^p, is related to deviatoric stresses S_{ij}, effective stress σ_e and effective plastic strain ε_p (the notation is slightly different from Section IV with ε_{ij}^p reserved for plastic strain) by Hencky's law (e.g., [21])

$$\varepsilon_{ij}^p = \frac{3S_{ij}}{2\sigma_e}\varepsilon_p. \tag{31}$$

Following a reasoning similar to (23), the composite average stress due to the temperature change is zero, therefore

$$c\sigma_{ij}^I + (1-c)\sigma_{ij}^M = 0. \tag{32}$$

It is important to note that the plasticity does not contribute to the volumetric strain. After substituting (29) and (30) into (28), and expressing of all the stresses in terms of that of the particles via (32), we have, by comparison of (27) and (28)

$$\overline{\alpha} = c\alpha^I + (1-c)\alpha^M + \frac{c}{3}\left(\frac{1}{K^M} - \frac{1}{K^I}\right)\frac{\sigma^I}{\Delta T}. \tag{33}$$

Similar to the procedures described in Section IV, the key to obtain the effective CTE of the composite systems then relies on the solution of the average stress in the particle phase, that provides a proper mechanism to account for inclusion interactions. This can be again accomplished through the Mori–Tanaka's Method.

VI. Conclusion

The pressure-induced conducting mechanisms are investigated first. The deformation analysis reveals a logarithmic pressure-resistance relationship and is capable of addressing the conducting phenomena for both rigid and deformable particle systems within a contact mechanics framework. It is observed that electrical contacts are made by squashing conducting particles for a deformable particle system while the particle penetration creates a crater in metallization to make contacts for a rigid particle system. The current analysis provides simple closed-form solutions for the elastic deformation of single-particle contacts and based on the assumption that the contact forces are evenly distributed in a conductive film, the pressure-resistance responses are correlated to the particle volume fraction. The high volume fraction, while ensuring that there are a sufficient number of particles to make contacts, may limit the particle deformation due to overall increased stiffness, resulting in the increased resistance on a per particle basis. The current analysis also offers insight into design considerations whereby limited amount of deformation (low processing temperature) and sufficiently low electrical resistance are to be simultaneously satisfied. For the mechanical performance, the uniaxial nonlinear stress–strain relationship is obtained for conductive adhesive systems in terms of polymer and particle material properties. The Mori–Tanaka's method is utilized to account for particle–particle and particle–matrix interactions. The behavior in thermal expansion within the elasto-plastic deformation range is also obtained in a similar fashion. In all these calculations, only a very simplified finite element analysis for the problem of a particle embedded into an infinitely extended matrix material needs to be carried out.

Conductive adhesive system is a complex composite material. A full understanding of the electrical and mechanical behavior of conductive adhesive materials requires the resolution of several key issues, including curing characteristics during assembly, quality of interfaces among matrix and particles, and their mating conditions to metallization. For the pressure-induced conducting mechanisms, one has also to consider the film resistance arising from particle oxidation. Some of these issues will constitute a part of our future endeavors.

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Kai X. Hu received the Ph.D. degree in mechanical engineering from the University of Arizona, Tucson, in 1993.

He joined Motorola Applied Simulation and Modeling Research Group, Schaumburg, IL, in 1994 and most recently as a Senior Staff Engineer. He has published more than 30 papers in refereed journals and a similar number of conference papers in the area of electronic packaging and solid mechanics.

Dr. Hu received the Applied Simulation and Modeling Award of Excellence, for his work at Motorola in 1996.

Chao-Pin Yeh received the Ph.D. degree from the School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, in 1992.

Since graduation, he has been employed with the High-Performance Packaging Division, IBM, Endicott, NY, for one and a half years before joining Motorola, Schaumburg, IL, in April 1993. Currently, he is a Supervisor of the Reliability and Quality Methodology Group, Motorola's Applied Simulation and Modeling Research Group, Motorola Corporate Software Center, Schaumburg. His research interests encompass finite element modeling, reliability prediction methodologies, design optimization, engineering database, design tool integration, and concurrent engineering with an emphasis in electronic packaging applications. He has published more than 30 conference papers and technical reports.

Karl W. Wyatt received the M.S. and Ph.D. degrees in electrical engineering at the Massachusetts Institute of Technology, Cambridge.

He is the Manager of the Applied Simulation and Modeling Research Group, Motorola Corporate Software Center, Schaumburg, IL. He is responsible for the development of a variety of strategic technologies for new products and systems. His organization includes specialists in the areas of electrical, mechanical, optical, and software engineering. Before joining Motorola in 1990, he worked at AT&T Bell Laboratories, Murray Hill, NJ and Reading, PA. He developed software which was used to solve the coupled, nonlinear Shrodinger–LaPlace equations for arbitrary heterojunction compound semiconductor FET's. He went on to supervise AT&T's Digital GaAs IC Design Group, having responsibility for DARPA III GaAs Pilot Line IC's, internal AT&T product applications, and commercial OEM high speed digital system applications.